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SINGLE DILEPTON PRODUCTION AT e^+e^-, $e\gamma$ AND $\gamma\gamma$ COLLIDERS

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Abstract

We calculate the cross sections for the single production of doubly-charged dileptons, both scalar and vector, at e^+e^-, $e\gamma$ and $\gamma\gamma$ colliders at $\sqrt{s} = 500$ GeV and 1 TeV. The $e\gamma$ mode is by far the most promising – dileptons whose coupling is as weak as $O(10^{-4})\alpha_{em}$ can be observed, for masses virtually up to the kinematic limit. Dileptons of mass up to $\sqrt{s}$ can also be seen in e^+e^- and $\gamma\gamma$ colliders, for couplings of order α_{em}. In all three colliders, most of the cross section comes from events in which the only particles detected are e^-e^-, the decay products of the dilepton, yielding an unmistakeable experimental signature.

Virtually all models of physics beyond the standard model (SM) predict the existence of new, exotic particles. Over the past several years, an enormous amount of effort has gone into exploring the possibilities for the detection of such particles at present and future colliders. In one interesting class of models, the gauge group for leptons is expanded from the $SU(2)_L$ of the SM to $SU(3)$. This happens, for example, in $SU(15)$ grand unified theories [1], or in models with an $SU(3)_L \times U(1)$ gauge symmetry [2]. In such models one finds dileptons (X^{--}, X^{-}), bosons (scalar or vector) which couple to pairs of leptons. Their masses might very well be low enough that these particles could be produced directly in the next generation of particle accelerators [3], [4].

Among future colliders, one of the most interesting is a high-energy linear e^+e^- collider. Not only does it provide a clean environment, but there is also the possibility of backscattering laser light off one or both of the beams [5], creating an $e\gamma$ or $\gamma\gamma$ collider.

In this paper, we will examine the single production of doubly-charged dileptons at such colliders. Rizzo has already taken a first step in this calculation – in Ref. [3] he presents the cross sections for both single and pair production of scalar dileptons at high-energy e^+e^- colliders, noting that, for a large range of masses and couplings, single production of dileptons dominates over pair production. We go beyond Rizzo's work in three ways. First, we consider both scalar and vector dileptons. Second, we compute the production cross section for all three collider modes: e^+e^-, $e\gamma$ and $\gamma\gamma$. The third point is a bit more technical – these cross sections are infrared divergent in the limit as $m_e \to 0$. We make an improvement to the procedure of regulating this divergence, which results in an increase in the cross sections by a factor of 3-5 relative to Rizzo's results. We will discuss this last point in more detail below.

At present, the constraints on the dilepton mass are not very stringent [6]-[8]. The strongest bound on the mass of doubly-charged vector dileptons comes from low-energy Bhabha scattering [6]: $M_X/g_{3l} > 340$ GeV (95% C.L.), while the mass of singly-charged vector dileptons must obey $M_X/g_{3l} > 640$ GeV (90% C.L.) from polarized muon decay [7]. Here, g_{3l} is the $SU(3)$ gauge coupling constant, which is expected to be of the same order of magnitude as the SM gauge couplings. For example, $g_{3l} = 1.19e$ for the $SU(15)$ GUT [1], and $g_{3l} = 2.07e$ in the $SU(3)_L \times U(1)$ model [2]. Thus, the doubly-charged dilepton mass must be greater than only $O(100)$ GeV. (Of course, if the mass difference between the singly- and doubly-charged dileptons is large, there will be significant constraints from the oblique electroweak parameters [9].)

The Lagrangian describing the interactions of doubly-charged vector and scalar dilep-

tons is

$$\mathcal{L}_X = -\frac{g_{3l}}{\sqrt{2}} X_\mu^{++} e^T C \gamma^\mu \gamma_5 e + \frac{g}{\sqrt{2}} X^{++} e^T C (1 - \lambda\gamma_5) e + h.c. \tag{1}$$

In the above, the vector coupling of the vector dilepton vanishes by Fermi statistics. Also, the coupling of the scalar dilepton is necessarily chiral, since it couples to two left-handed or right-handed electrons [3], so that $\lambda = \pm 1$. In the following, we shall take the two couplings, g_{3l} and g, to be completely arbitrary, although, as mentioned above, it should be remembered that g_{3l} is expected to be $\sim e$.

The diagrams which lead to single dilepton production in $e\gamma$ colliders are shown in Fig. 1. These are also the diagrams which dominate single dilepton production in e^+e^- and $\gamma\gamma$ colliders. In e^+e^- colliders, an energetic virtual photon is emitted from the e^+ beam, leading to the $e^-\gamma$ collisions of Fig. 1. The total cross section is then obtained by using the effective photon approximation. That is, the cross section for the process $e^-\gamma \to X^{--}e^+$ is folded together with the photon distribution function to give $\sigma_{ee}(s)$, the cross section for the process $e^+e^- \to X^{--}e^+e^+$ at centre-of-mass energy $\sqrt{s}$:

$$\sigma_{ee}(s) = \int_{s_{th}/s}^{1} d\tau f_\gamma(\tau) \hat{\sigma}(\tau s). \tag{2}$$

Here, $\hat{\sigma}(\tau s)$ is the cross section for the sub-process $e^-\gamma \to X^{--}e^+$ at centre-of-mass energy $\sqrt{\hat{s}}$, with $\hat{s} = \tau s$, and $\sqrt{s_{th}}$ is the threshold energy for the production of the final states in this process. The photon distribution function $f_\gamma(\tau)$ is given by [10]:

$$f_\gamma(\tau) = \frac{\alpha_{em}}{2\pi} \left\{ \frac{\left[1 + (1-\tau)^2\right]}{\tau} \ln\left[\frac{s \quad (1 - 2\tau + \tau^2)}{4m_e^2 (1 - \tau + \tau^2/4)} \right] + \tau \ln\left(\frac{2-\tau}{\tau}\right) + \frac{2(\tau-1)}{\tau} \right\} . \tag{3}$$

Similarly, in $\gamma\gamma$ colliders, one of the photons turns into a real e^+ (which is soft) and a virtual energetic e^-. The total cross section is then obtained by using the effective fermion approximation:

$$\sigma_{\gamma\gamma}(s) = 2 \int_{s_{th}/s}^{1} d\tau f_e(\tau) \hat{\sigma}(\tau s), \tag{4}$$

in which $\sigma_{\gamma\gamma}(s)$ is the total cross section for the process $\gamma\gamma \to X^{--}e^+e^+$ at centre-of-mass energy $\sqrt{s}$, and a factor of 2 has been included since the e^- can be emitted from either photon. The effective fermion function is given by [11]

$$f_e(\tau) = \frac{\alpha_{em}}{2\pi} \left\{ \left[\tau^2 + (1-\tau)^2\right] \ln\left[\frac{s}{4m_e^2} (1-\tau)^2 \right] + 2\tau(1-\tau) \right\} . \tag{5}$$

Note that there are other diagrams leading to single dilepton production in both e^+e^- and $\gamma\gamma$ colliders. However, the presence of the term $\ln(s/4m_e^2)$ in both the effective photon and effective fermion functions leads to a large enhancement of the contributions of the diagrams in Fig. 1 relative to these other diagrams. The error incurred by neglecting the other diagrams is estimated to be only about 5% [11].

From the above discussion, it is clear that the most important step in the calculation is the computation of the diagrams in Fig. 1. Before presenting the results, let us first address a key detail. If the mass of the electron is neglected, the second diagram in Fig. 1 diverges. This happens in that region of phase space in which the 3-momentum of the final e^+ is parallel to that of the initial photon. One way to deal with this is to impose a p_T cut of, say, 10 GeV on the final electron [3]. While this solves the problem, a large fraction of the total cross section is eliminated in the process. An alternative procedure, which is the one used in this paper, is to use the nonzero electron mass as the regulator [12]. (In this case, $s_{th} = (M_X + m_e)^2$ in Eqs. (2) and (4).) As we will see, this results in a substantial increase in the cross section compared to the p_T-cut procedure. Note that, regardless of the collider mode (e^+e^-, $e\gamma$ or $\gamma\gamma$), this increase corresponds to the inclusion of events which are completely collinear, *i.e.* events in which the X^{--} and the other final-state particle(s) go down the beam pipe. However, this does not create any experimental problems. Since the dilepton will then decay to e^-e^-, as far as the detector is concerned the process is effectively e^+e^- (*or* $e\gamma$ *or* $\gamma\gamma$) $\to e^-e^-$, giving a signal which is unmistakable, and has, of course, virtually no SM background.

The cross sections for single dilepton production at e^+e^-, $e\gamma$ and $\gamma\gamma$ colliders are presented for two values of the centre-of-mass energy, $\sqrt{s}$ = 500 GeV and 1 TeV. We assume the integrated luminosity at all 3 colliders to be 10 fb^{-1} at 500 GeV, and 60 fb^{-1} at 1 TeV. As a figure of merit, we require 25 events for discovery, which corresponds to a cross section of 2.5 fb at $\sqrt{s} = 500$ GeV and 0.4 fb at 1 TeV. Note that we consider *only* X^{--} production. If one includes both X^{--} and X^{++} production, the cross sections must be multiplied by a factor of 2.

We focus first on the scalar dileptons, X_S. We parametrize the strength of the dilepton coupling by comparing it to the electromagnetic interaction, *i.e.* $g^2 = 4\pi k_S \alpha_{em}$, and allowing k_S to vary. The cross section for $e^-\gamma \to X_S^{--} e^+$ is found to be

$$\sigma_S(s) = \frac{\pi k_S \alpha_{em}^2}{s^2} \left[\beta \left(\frac{3}{2}s + \frac{17}{2}M_X^2 \right) + 8M_X^2 \ln \left[\frac{2-\alpha-\beta}{2-\alpha+\beta} \right] + \frac{\left(s^2 - 2M_X^2(s - M_X^2)\right)}{s} \ln \left[\frac{\alpha+\beta}{\alpha-\beta} \right] \right], \tag{6}$$

independent of the chirality of the scalar dilepton coupling. In the above,

$$\alpha \equiv 1 - \frac{(M_X^2 - m_e^2)}{s} \tag{7}$$

and

$$\beta \equiv \left(1 - 2\frac{(M_X^2 + m_e^2)}{s} + \frac{(M_X^2 - m_e^2)^2}{s^2}\right)^{\frac{1}{2}} . \tag{8}$$

The above cross section is written in such a way that it is clear that $\sigma_S(s) \to 0$ as the kinematic limit $\beta \to 0$ is reached. Away from the kinematic limit, the logarithms in Eq. (6) can be written in the more transparent forms:

$$\begin{aligned} \ln\left[\frac{\alpha+\beta}{\alpha-\beta}\right] &\to \ln\left[\frac{(s-M_X^2)^2}{s\, m_e^2}\right], \\ \ln\left[\frac{2-\alpha-\beta}{2-\alpha+\beta}\right] &\to \ln\left[\frac{M_X^2}{s}\right]. \end{aligned} \tag{9}$$

A comparison of the two regulation procedures — a nonzero m_e and a 10 GeV p_T cut — is straightforward. Eq. (6) still holds when a p_T cut is used, with (i) the replacement of m_e in Eq. (9) by p_T and the neglect of m_e everywhere else, and (ii) the addition of a single finite piece, $(\pi k_S \alpha_{em}^2/s^2)\beta(s+M_X^2)$. This agrees with the results of Ref. [3]. By comparing $\ln(s/m_e^2)$ with $\ln(s/p_T^2)$ (these are typically the largest contributions), one sees that one gains a factor of roughly 3-5 by using m_e as a regulator. This expectation is borne out quantitatively, as we will see below.

The cross section for the process $e^-\gamma \to X_S^{--}e^+$ with dilepton coupling strength $k_S = 1$ is shown in Fig. 2, as a function of the dilepton mass, M_X. At both $\sqrt{s} = 500$ GeV and 1 TeV, for virtually the entire range of M_X, the production cross section is orders of magnitude above the cross sections required for discovery (2.5 fb at $\sqrt{s} = 500$ GeV, 0.4 fb at 1 TeV). In other words, for $k_S = 1$, dileptons with masses essentially up to the kinematic limit will be easily observable. Since the cross section is linear in k_S, it is straightforward to scale the results shown in Fig. 2 to other values of k_S. This shows that scalar dileptons of $M_X \lesssim \sqrt{s}$ with couplings as small as k_S = 5-7 $\times 10^{-4}$ can be seen in high-energy $e\gamma$ collisions.

In Fig. 3 we present the cross sections for the process $e^+e^- \to X_S^{--}e^+e^+$, for three values of the coupling, $k_S = 1$, 0.1 and 0.01. To calculate these cross sections, we use the effective photon approximation described by Eq. (2) above. In Figs. 3a and 3b the straight line corresponds to the assumed discovery cross section. Thus, for example, at

$\sqrt{s} = 1$ TeV, dileptons with coupling strength $k_S = 1$ (or $k_S = 0.1$ or .01) can be seen for $M_X \lesssim 990$ GeV (or $M_X \lesssim 950$ GeV or 700 GeV). We have also calculated these cross sections using a p_T cut to regulate the forward divergence, and we reproduce the results of Rizzo [3]. By comparing the results shown in Fig. 3 with those in Ref. [3] (remembering that in Ref. [3] there is an additional factor of 2 due to both X_S^{--} and X_S^{++} production), we see that the procedure of using a nonzero m_e as a regulator does indeed increase the cross section by a substantial factor compared to the p_T-cut procedure.

Finally, Fig. 4 shows the cross sections for $\gamma\gamma \to X_S^{--}e^+e^+$, for $k_S = 1$, 0.1 and 0.01. These cross sections have been calculated using the effective fermion approximation (Eq. (4)). Comparing Fig. 4 to Fig. 3, we note that, for most values of M_X, single dilepton production in e^+e^- collisions is greater than that in $\gamma\gamma$ collisions. It is only for values of M_X quite close to $\sqrt{s}$ that the cross section for $\gamma\gamma \to X_S^{--}e^+e^+$ exceeds that for $e^+e^- \to X_S^{--}e^+e^+$. However, when one takes into account that the luminosity of a $\gamma\gamma$ collider is at most 80% of the parent e^+e^- collider, one concludes that the e^+e^- mode is better than the $\gamma\gamma$ mode for single dilepton production. (Of course, neither can compete with the $e\gamma$ mode, as is clear from Fig. 2.)

We now turn to vector dileptons, X_V. As was done in the case of scalar dileptons, we parametrize the strength of the coupling as $g_{3l}^2 = 4\pi k_V \alpha_{em}$. (However, it should be remembered that, since g_{3l} is a gauge coupling, k_V is expected to be ~ 1.) The cross section for $e^-\gamma \to X_V^{--}e^+$ is given by

$$\begin{aligned}\sigma_V(s) = \frac{\pi k_V \alpha_{em}^2}{s}\Bigg\{&\beta\left(2 + \frac{8s}{M_X^2} + \frac{13}{2}\frac{M_X^2}{s}\right) + \frac{(s^2 - 2sM_X^2 + 2M_X^4)}{s^2}\ln\left[\frac{\alpha+\beta}{\alpha-\beta}\right] \\ &+ \frac{\left(-s^3 + 12s^2M_X^2 + 18sM_X^4 - 4M_X^6\right)}{2s^2M_X^2}\ln\left[\frac{2-\alpha-\beta}{2-\alpha+\beta}\right]\Bigg\},\end{aligned} \tag{10}$$

where α and β are defined in Eqs. (7) and (8).

The cross section for $e^-\gamma \to X_V^{--}e^+$ with $k_V = 1$ is shown in Fig. 5. As was the case for scalar dileptons, at both $\sqrt{s} = 500$ GeV and 1 TeV the cross sections are enormous, so that dileptons with masses almost up to the kinematic limit are easily observable. Indeed, vector dileptons with couplings as small as $k_V = 3\text{-}4 \times 10^{-4}$ can be seen in $e^-\gamma \to X_V^{--}e^+$.

In Figs. 6 and 7 we present the cross sections for the processes $e^+e^- \to X_V^{--}e^+e^+$ and $\gamma\gamma \to X_V^{--}e^+e^+$, respectively, for three values of the coupling, $k_V = 1, 0.1$ and 0.01. In both processes, for $k_V \sim 1$, which is favoured, dileptons with masses virtually up to the kinematic limit are observable. As was the case for scalar dileptons, a comparison of Figs. 6 and 7 reveals that the production cross section in e^+e^- mode is greater than that

in $\gamma\gamma$ mode for most values of M_X. Therefore, e^+e^- collisions are better than $\gamma\gamma$ collisions for producing single vector dileptons.

To summarize, we have calculated the single production of dileptons, both scalar and vector, in e^+e^-, $e\gamma$ and $\gamma\gamma$ colliders at $\sqrt{s} = 500$ GeV and 1 TeV. In e^+e^- and $\gamma\gamma$ collisions, the contribution from the subprocess $e^-\gamma \to X^{--}e^+$ dominates the production cross section. We have used the nonzero electron mass to regulate the infrared divergence in that region of phase space in which the momenta of the final e^+ and the initial γ are parallel. This results in an increase in the cross section by a factor of 3-5 compared to the method of putting a p_T cut on the final e^+. With this method, most of the cross section comes from events which go down the beam pipe. However, this causes no problems – when the dilepton decays, this results in an unmistakeable signal in the detector: e^+e^- (*or* $e^-\gamma$ *or* $\gamma\gamma$) $\to$ e^-e^-, which is virtually background-free.

Of the three colliders, the $e\gamma$ mode is by far the most promising – scalar and vector dileptons with masses up to essentially $\sqrt{s}$, and whose coupling strength is equal to α_{em}, will be copiously produced in the process $e^-\gamma \to X^{--}e^+$. In fact, it will be possible to detect dileptons whose coupling strength is as small as $O(10^{-4})\alpha_{em}$. As for e^+e^- and $\gamma\gamma$ colliders, even though the cross sections for single dilepton production are much smaller here than they are in the $e\gamma$ collider, it is still possible to detect dileptons with masses up to the kinematic limit, for a dilepton coupling strength equal to α_{em}. Even dileptons whose coupling is weaker are detectable over a large range of masses. It should also be noted that, for a given dilepton mass, the production cross section is greater in e^+e^- colliders than in $\gamma\gamma$ colliders.

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Figure Captions

- *Figure (1):* The three diagrams contributing to the process $e^-\gamma \to X^{--}e^+$.

- *Figure (2):* Cross section for the process $e^-\gamma \to X_S^{--}e^+$ at (a) $\sqrt{s} = 500$ GeV, and (b) $\sqrt{s} = 1$ TeV, for $k_S = 1$.

- *Figure (3):* Cross section for the process $e^+e^- \to X_S^{--}e^+e^+$ at (a) $\sqrt{s} = 500$ GeV, and (b) $\sqrt{s} = 1$ TeV, for $k_S = 1$ (solid line), $k_S = 0.1$ (dash-dot line) and $k_S = 0.01$ (dashed line). The horizontal line is the (assumed) discovery cross section of 2.5 fb (0.4 fb) at $\sqrt{s} = 500$ GeV (1 TeV).

- *Figure (4):* Cross section for the process $\gamma\gamma \to X_S^{--}e^+e^+$ at (a) $\sqrt{s} = 500$ GeV, and (b) $\sqrt{s} = 1$ TeV, for $k_S = 1$ (solid line), $k_S = 0.1$ (dash-dot line) and $k_S = 0.01$ (dashed line). The horizontal line is the (assumed) discovery cross section of 2.5 fb (0.4 fb) at $\sqrt{s} = 500$ GeV (1 TeV).

- *Figure (5):* Cross section for the process $e^-\gamma \to X_V^{--}e^+$ at (a) $\sqrt{s} = 500$ GeV, and (b) $\sqrt{s} = 1$ TeV, for $k_V = 1$.

- *Figure (6):* Cross section for the process $e^+e^- \to X_V^{--}e^+e^+$ at (a) $\sqrt{s} = 500$ GeV, and (b) $\sqrt{s} = 1$ TeV, for $k_V = 1$ (solid line), $k_V = 0.1$ (dash-dot line) and $k_V = 0.01$ (dashed line). The horizontal line is the (assumed) discovery cross section of 2.5 fb (0.4 fb) at $\sqrt{s} = 500$ GeV (1 TeV).

- *Figure (7):* Cross section for the process $\gamma\gamma \to X_V^{--}e^+e^+$ at (a) $\sqrt{s} = 500$ GeV, and (b) $\sqrt{s} = 1$ TeV, for $k_V = 1$ (solid line), $k_V = 0.1$ (dash-dot line) and $k_V = 0.01$ (dashed line). The horizontal line is the (assumed) discovery cross section of 2.5 fb (0.4 fb) at $\sqrt{s} = 500$ GeV (1 TeV).

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